Development and Testing of Robotic Inspection Tools for the High-Level Waste Double Shell Tanks at Hanford– 17292

Anthony Abrahao, Dwayne McDaniel, Ryan Sheffield, Michael DiBono, Yew Teck Tan
Applied Research Center - FIU

ABSTRACT

Florida International University (FIU) has been developing inspection tools that are capable of accessing the tank floors of double shell tanks through air supply lines and air refractory channels. This effort has led to the development of a pneumatic pipe crawler and a miniature rover. The miniature rover is a remote controlled vehicle with four wheels directly driven by independent micro DC motors.. The rover will have to navigate through channels as small as 3.81 cm by 3.81 cm, and includes turns with angles up to 90°. To avoid debris, the device travels upside down, magnetically attached to the bottom of the primary tank. The pneumatic pipe crawler is a snake type robot with a modular design. The design is an evolution of previous peristaltic crawlers developed at FIU, and uses pneumatic actuators to emulate the contractions of the peristaltic movements. The inspection path consists of approximately 30 m of pipe (7.62 and 10.16 cm in diameter), reducers and several elbows. In this paper, engineering scale testing of the both systems is presented. Slight modifications have also been made to the designs, based on the testing, and are also explained. The engineering scale testing of the crawler includes approximately 30 m of piping that has the same lengths, dimensions and fittings as the air supply line of AY-102. The primary difference is that that actual line has a number of sections that are vertical. Testing of the miniature rover has included a testbed manufactured with brick pavers, providing more realistic coefficients of friction between the tether and the channel. Efforts to reduce the load induced when the tether is in contact with a corner in the refractory channel will also be provided.

INTRODUCTION

In August of 2012, traces of waste were found in the annulus of the AY-102 double-shell tank storing radioactive waste at the DOE Hanford site, prompting the need for developing inspection tools that can identify the cause and location of the leak. Fig. 1 shows three possible entry points for inspection in the AY-102 double-shell tank:

1. the refractory air slots through the annulus,
2. the leak detection piping, and
3. the ventilation header piping.

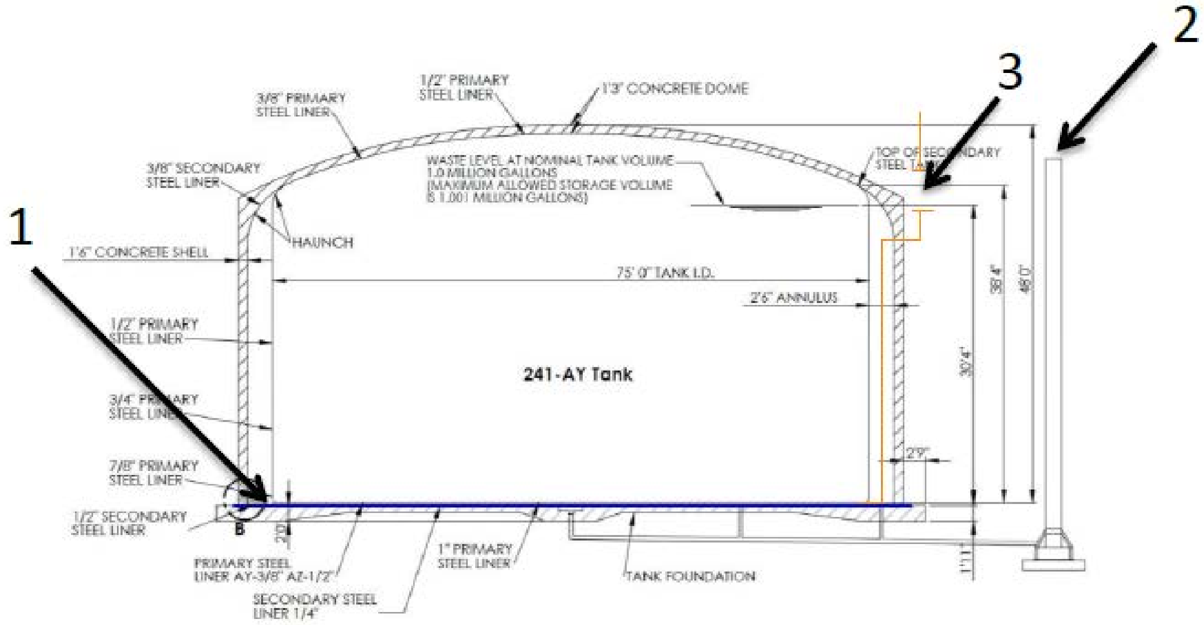

Fig. 1. Inspection entry points of the AY-102 double-shell tank.

To assist in this effort, Florida International University is investigating the development of inspection tools able to access into the tank secondary containment, while providing live visual feedback. The effort led to the development of two inspection tools:

- a ***magnetic miniature rover*** that will travel through the refractory air slots, and
- a ***pneumatic pipe crawler*** that will inspect the ventilation header piping.

The objective of this research effort is to develop inspection tools that will assist site engineers at Hanford in understanding the health of the DSTs and to provide a means to identify the source of the material entering the annulus space of AY-102.

Magnetic Miniature Rover

FIU is developing a technology that will access the primary tank floor of DSTs at Hanford through the annulus and refractory air slots (Fig. 2) and provide visual feedback of the condition within the air slots. The refractory air slots range from 2.54 cm to 7.62 cm in width and provide a complex maze to navigate through, including four 90° turns to reach the center of the tank (Fig. 3). Pictured is documentation on AY-102, a tank possessing one of the more difficult inspection paths due to the layout of the refractory cooling channels; other double-shell tanks contain channels whose layouts resembles a web structure with much larger angles at the turns rather than the sharp 90° turns.

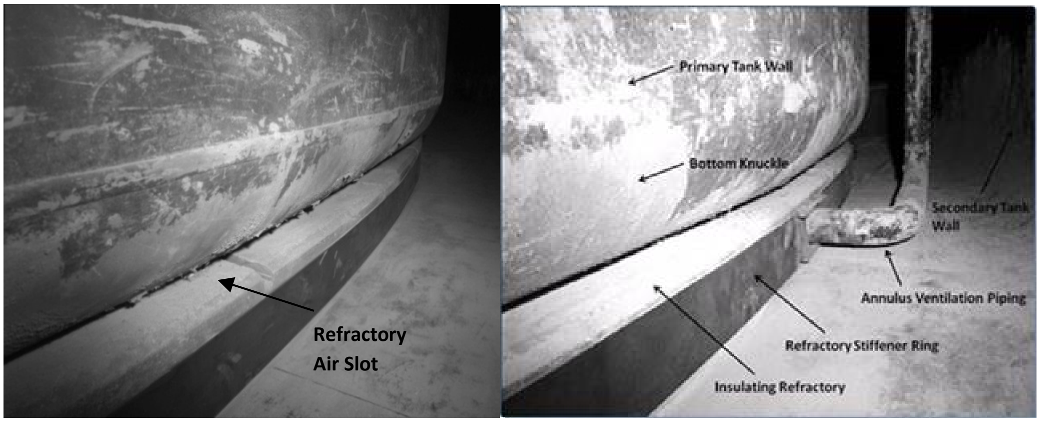

Fig. 2. Side view of primary tank and refractory air slot.

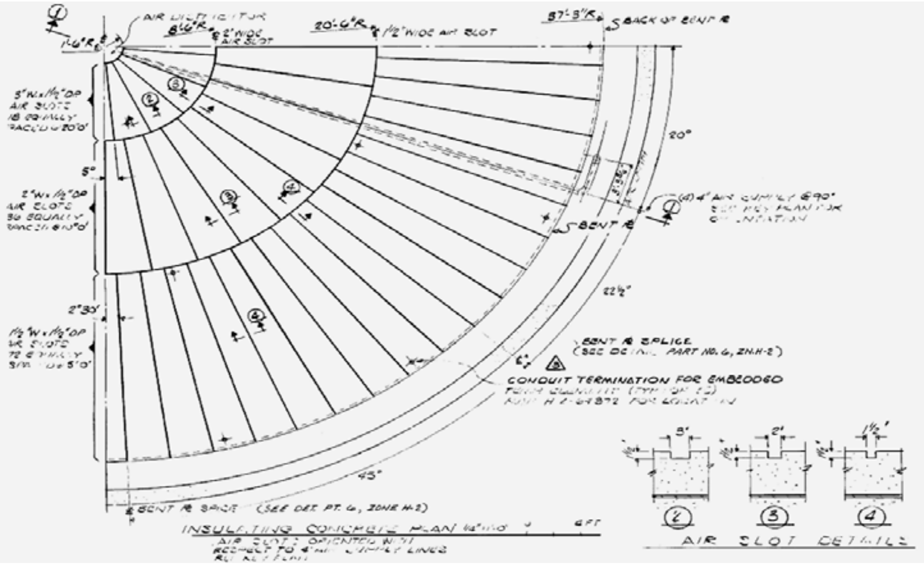

Fig. 3. Refractory air slot layout and description for AY-102.

In conjunction with site engineers, FIU has gathered information that has been used to establish the design specifications for the inspection tool. This includes annulus and refractory air slot geometry and maximum temperature and radiation limits for the device. Discussions with the engineers on the condition of the carbon steel along the tank bottom led to the viewing of refractory air channel video inspections for tanks AW-101, AZ-102, and SY-103 that were performed ten years ago with an articulated robot inside the annulus. The video provided FIU with a general idea of the conditions that will be encountered in the air channels, as well as the primary tank bottom surface condition. The video also provided FIU with a better understanding of the refractory pad's low shear strength and how easy it is to create debris (Fig. 4).

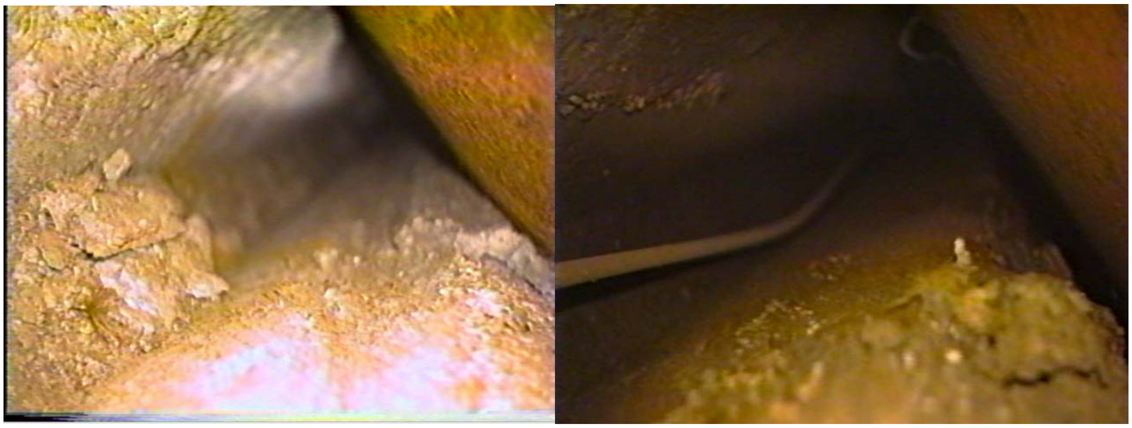

Fig. 4. Debris seen in refractory air slots.

A prototype inspection tool was initially designed and the proof-of-concept was validated via bench scale testing. Initial efforts have focused on creating a design that can navigate the first 5.2 m of the AY-102 refractory slots. After AY-102 was drained, efforts were moved to designing a tool that could navigate through the web type configurations, reducing the constraints on the length of the unit and the friction on the tether. After a number of bench scale tests, various design modifications have been implemented. Efforts in improving the design have been focused on minimizing the complexity of the design while retaining efficiency [1].

One of main areas for needed improvement in the inspection tool was for the wheels that endure notable damage under prolonged heavy use. This was due to the moment caused by the magnetic force, combined with the transverse loads experienced when turning the rover while the wheels remained straight at all times. These strenuous and cyclic loads took a toll on the narrow wheels and while the wheels were able to withstand the static loading, the cyclic loading experienced during stress testing induced damage that affected the inspection tool performance. This critical observation was addressed in the following design iteration shown in Fig. 5. Previously, the inspection tool wheels were designed as narrow as possible to minimize the width of the tool but with these detrimental cyclic loadings in mind, the width was increased, which also provided room to install a heat-set insert to allow for the wheels to be held to the shaft via a bolt. The wheels also relied on a press fit to attach to the motor shafts; however, the material was not able to sustain the cyclic loading and over time the press fit became less reliable. To allow for an increase in wheel width, any unnecessary space observed in the inspection tool was removed, and cavities in the body were created to allow for a more ergonomic wire management within the inspection tool. Most of the components of the rover are 3D printed and are shown in Fig. 6.

A cable management system is necessary to provide a tangle free means of storing/supplying the tether for the inspection tool. A first prototype of the cable management system was developed with a stepper motor as the primary driving force. A timing belt is used to coil the tether around its base and can adjust the gear ratio of the system (Fig. 7).

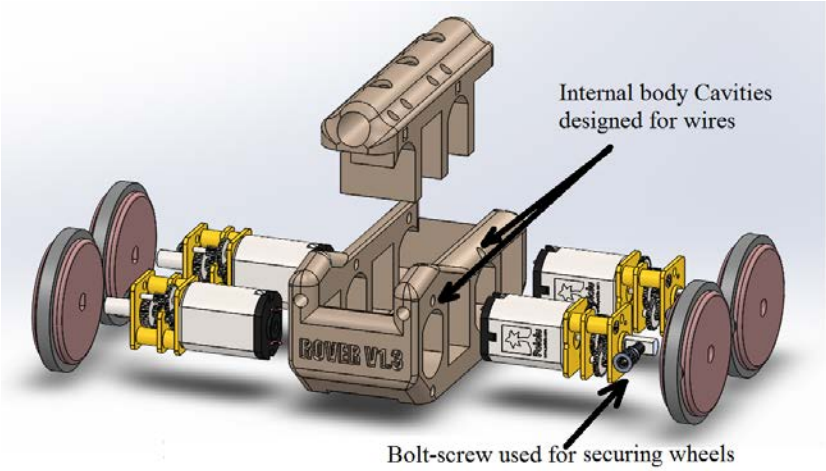

Fig. 5. Exploded view of the current design of the inspection tool.

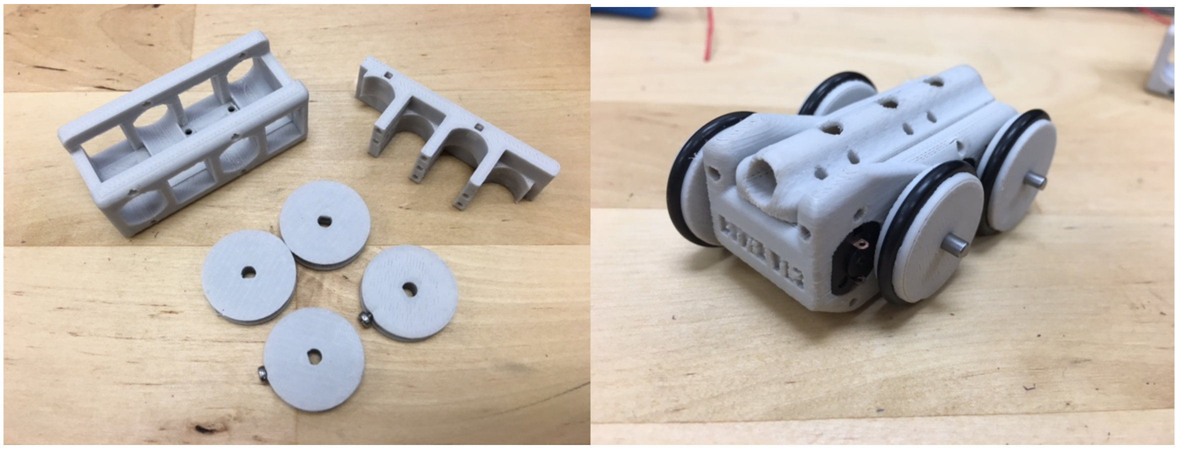

Fig. 6. 3D printed components (left), assembled inspection tool (right).

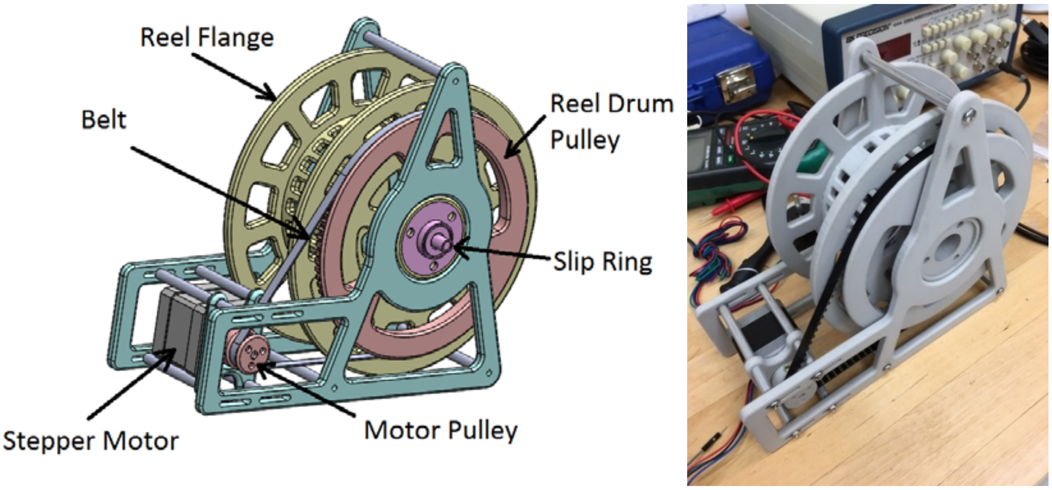

Fig. 7. Cable management system for inspection tool.

Miniature Rover Testing

The magnetic force provided by the magnets is of great interest due to its heavy influence in the inspection tools performance. The magnetic force must be balanced; too strong of a magnetic force can negatively affect the inspection tools performance, as can too weak of a magnetic force. The current motors used in the inspection tool provide enough power such that the bottleneck is no longer the motors, but converting the power delivered from the motors into translational motion of the inspection tool; the characteristic which this depends upon is the traction force which is proportional to the normal force. However, the rolling resistance is also directly proportional to the normal force. The influence of the rolling resistance is two-fold, as it is to be considered for both the added load on the motors when moving forward, as well as the resistance in the event that the inspection tool is pulled out of the channel via the tether. Manufacturer provided data includes the normal force provided by the magnets when there is no separation between the magnet and the surface; however, in this application, there will be a separation. Understanding how the magnetic force is related to the separation is crucial for magnet selection, as a balance must be struck between having sufficient traction and minimizing the force of the rolling resistance. Experimentation was performed on the magnets to determine the relation between the distance and the magnetic force. The test apparatus and results are shown in Fig. 8.

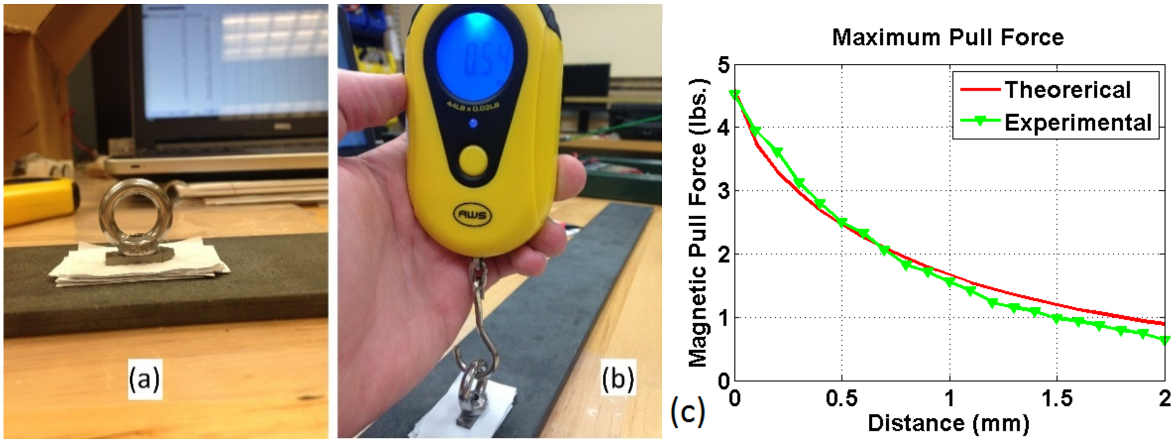

Fig. 8. Magnetic force testing and results.

For the miniature rover, testing and validations were also conducted with the objective of verifying the navigation of the inspection tool on curved surfaces. To date, the navigation of the inspection tool has only been verified on flat surfaces. These tests demonstrate the potential of the rover to provide inspections in carbon steel pipes as well as refractory channels. Complete results from this testing can be obtained from [2].

Following the pipe navigation testing, the miniature rover's performance was also evaluated using pipes with internal corrosion. This test was conducted inside five steel pipes that were 6.1 m in length and had 7.62 cm diameters. The 5 pipes that were used for the testing are shown in Fig. 9. Similar to the initial bench scale tests, the magnetic force and pulling capability of the inspection tool was significantly decreased. However, the tool was able to navigate through the 6.1 m of pipes.

Significant debris did build up on the magnets (Fig. 9) but this did not significantly affect the maneuverability of inspection tool. Another notable issue was the weight and drag from the tether which applied a moment on the body of the device and prevented the inspection tool from navigating in a straight path; this is an observation that may be addressed with a tether management system.

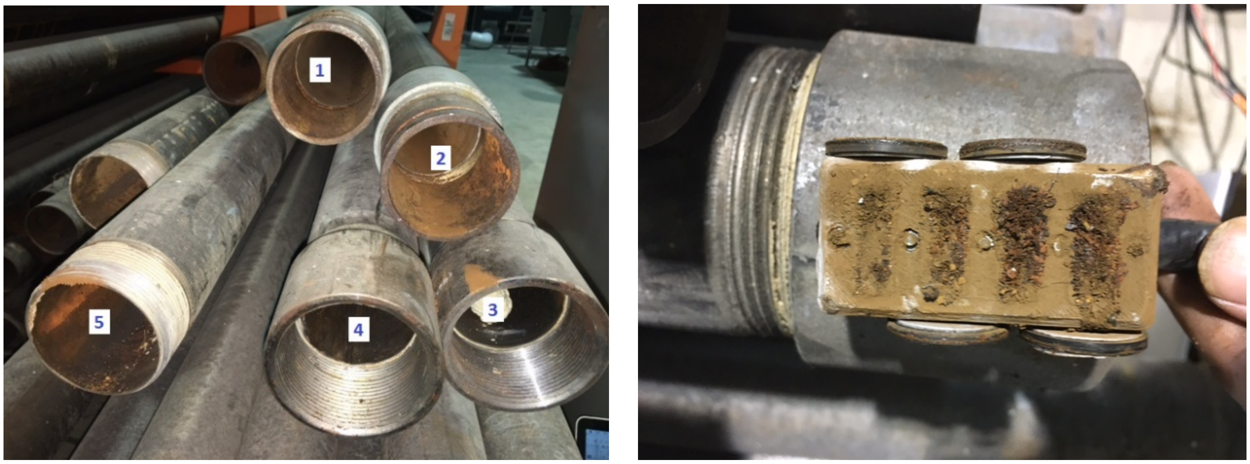

Fig. 9. The corroded pipes used for navigation test b) debris build up on the magnets after 30.5 m of navigation.

Another form of stress testing the inspection tool and placing it in imperfect environment was to attempt to navigate across large gaps; this serves as a simulation of the inspection tools maneuverability across a surface that may have cracks, inundations and any other surface imperfections. Testing was conducted over two separate pieces of steel plates aligned using a clamp. A gap was created by separating the steel plates from each other with an initial gap of 1 mm. After each successful test, the gap was increased. The maximum gap the inspection tool was able to overcome was 28.02 mm, almost half of length of the inspection tool (62.98 mm).

FIU also developed a new test set-up that can measure the pull force of the tether with more realistic materials and coefficients of friction. The test bed included 5.2 m of the 3.81 cm by 3.81 cm channels and two turns, one 90 degree turn at the end of channel and another turn 20.32 cm away. Fig. 10 shows the testbed that was constructed using brick pavers to provide more realistic friction forces.

The current tether pull force ranges from 12.5 to 19.6 N. When a smoother cable, such as a standard 13 wire cable with an insulated jacket was utilized, the average pull force was about 5.3 N. Since the geometry of the current inspection tool does not allow for 90 degree turns, the tool was manually placed after the first turn and on average was able to navigate 10.2 cm after the first turn.

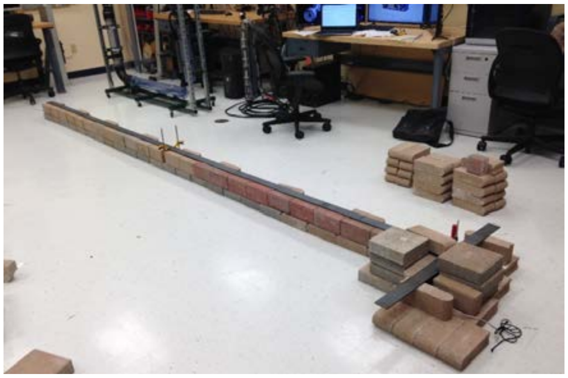

Fig. 10. Laboratory scale test bed created for determining the pull force created by tether.

Pneumatic Pipe Crawler

The pneumatic pipe crawler is an inspection tool designed to travel through the air supply line, leading to the central plenum of a typical DST at Hanford, and to provide live video feedback. For AY-102, the proposed inspection path is approximately 30.5 m from grade, down through one of the drop legs, and then lateral to the center bottom of the tank secondary containment, as sketched in Fig. 11 below. The route consists of all welded schedule 40 pipes (which are 7.62 and 10.16 cm in diameter), reducers and several elbows. The four drop legs branch from the "header ring" with a diameter of 7.62 cm, transitioning then to 10.16 cm.

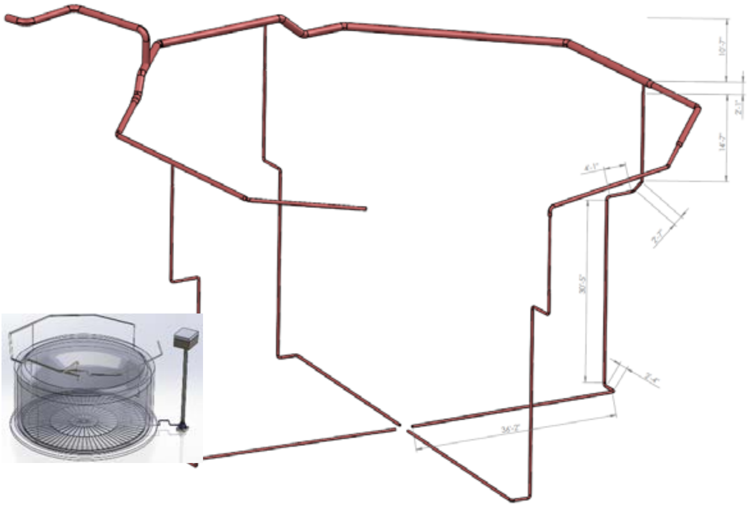

Fig. 11. AY-102 air supply lines.

The inspection route to the central plenum through the air supply lines has the following requirements:

a) Crawl through pipes and fittings (7.62 and 10.16 cm diameter)
b) Climb vertical runs
c) Tolerate elevated temperatures (76.6 ^{o}C)
d) Tolerate moderate radiation levels (85 rad/hr)
e) Provide a means for removal in the event of a malfunction

Additionally, the crawler will need to provide live video feedback as required; however, plans for carrying additional instrumentation are being investigated. The current design for the pipe crawler is a worm type robot with a modular design, composed of interchangeable cylindrical modules connected with flexible links. Fig. 12 shows a rendering of one of the more recent designs of the system.

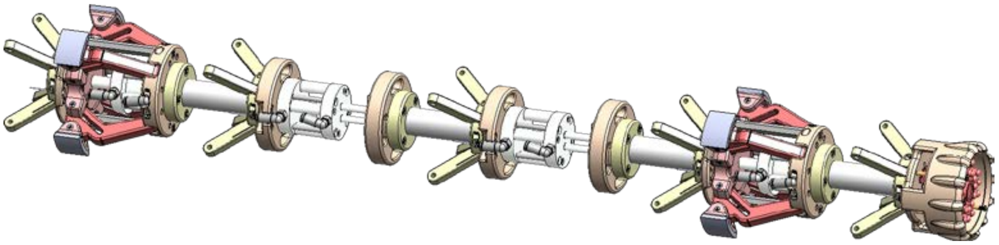

Fig. 12. FIU's pneumatic pipe crawler.

The design is an evolution of previous pipe crawlers developed at FIU [3]. The tool inherits the idea of using peristaltic propulsion, powered by pneumatics, and includes an innovative design with a modular approach that utilizes off-the-shelf pneumatic actuators to produce the contractions of the peristaltic motion. A pneumatic powered crawler is suitable for highly radioactive environments with potential exposure to flammable gases. The locomotion system does not require embedded radiation hardened electronics and electric actuators. The design is also inherently ignition proof, since pneumatic actuators are not likely to produce electric sparks common in some electric motors and actuators. In addition, a peristaltic propelled crawler offers an appropriate design for decontamination. The device can navigate inside a pipeline without using any external moving parts, such as wheels and continuous tracks, which could be designed to be fully encapsulated in a disposable elastic skin. In extreme cases, the crawler itself can be considered disposable, due to its affordable design. Another design advantage is associated with its modular design, which has the potential to be customizable. Other specific tasks could be accomplished with the addition of extra modules, such as instrumentation, material sampling, and pipe repair. The crawler's basic design is composed of five modules linked by flexible connections: a) the front camera, b) the front and back grippers, and c) the two middle expansion modules. The crawler also includes three additional components: a control box, a tether, and an instrumentation module which is currently being designed. The new module will use an embedded computer for instrument control and communication.

The expansion modules use compact nonrotating tie rod air cylinders to propel the crawler forward during the peristaltic movements of contraction and expansion. These cylinders have two parallel piston rods that prevent the rotation of the front camera, and house actuators that have 1.9 cm stroke, 1.9 cm bore diameter and are capable of producing 178 N of force at 690 kPa. The gripper modules are designed to grip pipes and fittings with internal diameters varying from 7.62 to 10.16 cm.

Maximizing the grip strength of the module was a major factor in the development of the crawler. Increased grip strength will allow the device to carry additional instrumentation, and to inspect longer pipelines, which will be critical when considering the crawler for other types of applications and inspections. Strong grips were obtained by increasing the number of claws per gripper and by redesigning the claws using hinged tips with cylindrical pads. As shown in Fig. 13, the redesigned claws also use extension springs to retrieve the pads when the mechanism closes, keeping a tight fit during crawling.

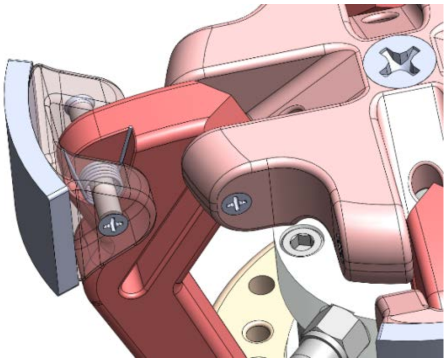

Fig. 13. Gripper claws with hinged pads.

The initial design provided a gripping force of approximately 80.1 N which was increased to 178 N with the aforementioned design modifications. The achieved grip of 178 N is equivalent to the maximum force in which the expansion modules can propel the crawler. However this maximum force may vary with the internal conditions of the pipe surface. The issue will be addressed during the mockup testing.

An electric version of the crawler is currently being considered and has the potential to develop stronger and smaller inspection tools. However, the output speed and force control are concerns that will need to be addressed.

The front camera module, shown in Fig. 14, carries a day-night 1.0 megapixel (720p) digital camera, with infrared cut-off filters and LEDs. The camera is an independent module, and can be easily replaced depending on the specific application. One of enhancements in the design of the front camera was the addition of external ribs to the case.

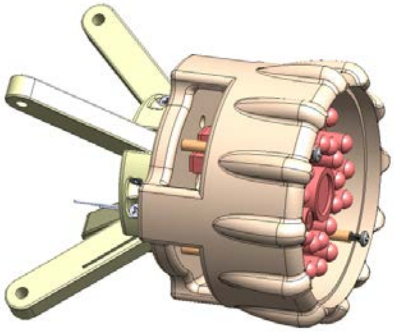

Fig. 14. Camera module.

The ribs, as illustrated in Fig. 15, assist the camera in overcoming slight fitting misalignments in the pipeline during a turning maneuver. However, a front guiding mechanism will need to be incorporated into the design if considerable misalignments are involved.

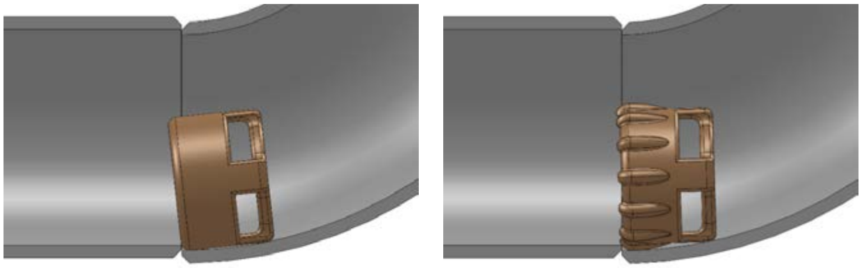

Fig. 15. Piping misalignment and front camera overcoming misalignment.

All modules are linked by flexible connections which have two crucial functions during maneuvers through pipes and fittings: 1) allow the unit to bend, and 2) keep the modules centered.

The original inspection tool uses small arms and torsion springs to keep the modules near the center of pipes and fittings, which minimizes bouncing and dragging of the unit. The guides also prevent the bulldozer effect (collection of debris) in the front camera. Fig. 16 shows the strengthened suspension guides. The addition of extension springs was necessary to compensate for the weak torsional springs used in the original design. Off-the-shelf torsional springs with adequate size/strength ratio were not available. The additional wheels reduce the dragging and assist in the removal of the crawler in the event of a failure. However they are not critical to the forward motion of the system.

Fig. 16. Strengthened suspension guides.

Fig. 17 shows a schematic of the portable control box. The box will be used for field deployment. The design is self-contained and includes panels which provide:

- quick disconnect for all pneumatic and electric lines,
- pressure regulator,
- pressure gauges,
- internet and USB access, and
- touch screen interface.

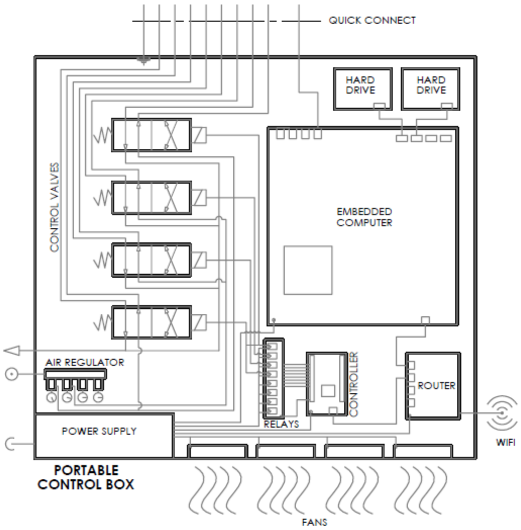

Fig. 17. Control box schematic.

With the control box, the crawler movement is fully automated and can be controlled remotely using any handheld device connected to the private wireless network of the box. The controlling software is customizable, which increases the versatility of the tool. Fig 18. shows the assembled control box including the cables, wires and controllers.

Fig. 18. Control box.

The speed of the crawler is determined by the peristaltic cycle. The cycle distance is defined by the displacement of expansion modules. The cycle time and the device speed is programmable; however, the maximum working frequency is influenced by the pressurization of the pneumatic lines and the tether length.

The tether required for the proposed inspection is approximately 30.5 m in length and 1.27 cm diameter and includes 8 pneumatic lines, 1 camera line, and 1 retrieval steel cable. The retrieval cable is responsible for carrying the pulling load, which relieves tension in the other lines of the tether. The bundle is also enclosed by an abrasion-resistant sleeve, which reduces friction and protects the cables from wear and tear. In the recent design of the crawler, an Ethernet cable has replaced the USB cable which provided live video feedback from the device. The network cable not only allows communication with the module, but also supplies electric power. With this change, additional smart sensors can be incorporated to the current design without the addition of extra cables and future modifications to the tether.

A new instrumentation module is currently being designed to provide sensor feedback from the crawler during inspections. The module will carry an embedded computer, a tether load cell, and additional sensors. The module uses the embedded computer for instrument control and communication, which also allows video streaming from the front camera. In the current stage of the design, the sensors being considered may provide feedback on orientation, altitude, pressure, temperature, humidity and radiation. In addition, there are plans to include nondestructive testing and inspection sensors, such as ultrasound for pipeline life assessment. Size and space issues were resolved with the use of a micro USB hub. The micro hub does not have the typical connectors for slave USB devices. The wires are soldered directly to it, which allows for the connection of several USB devices, such as cameras and sensors in a tiny space (3.56 cm x 2.03 cm). The hub also supports an external power supply, which overcomes other issues associated with the low power available directly from the embedded computer used in the module.

Pneumatic Crawler Testing

To validate the design concept and demonstrate the potential of the crawler, two bench scale testbeds were manufactured to evaluate various parameters of the crawler; this included the maximum pull force, and the system's maneuverability. Results from these tests can be found in (Lagos, et al., 2016).

To evaluate the performance of the pneumatic crawler, a full scale mockup of the ventilation system for AY-102 was manufactured. For full scale tests, the primary concern is the crawler's ability to manage the tether and to overcome the increasing drag force during the inspection. The path dimensions of the proposed inspection are shown in Fig. 11. The testbed, shown in Fig. 19 below, has a layout equivalent to one of the AY-102 ventilation risers. In the configuration, however, the initial vertical section runs horizontally, which is structurally cost effective, considering that approximately 18.3 m of piping would need to be vertically supported. In addition, the horizontal configuration will be more challenging, considering that during the vertical section, the crawler would be primarily gravity fed.

Fig. 20 shows preliminary pull force tests being conducted with the full-scale mockup. The tether was dragged through the pipeline, while the dragging force was measured with a hand scale. During these tests, the average recorded drag force was approximately 22.2 N. The levels eventually peaked around 35.6 N, which is well below the pull force of the crawler (178 N). However, pipe surface conditions, such as the presence of water, rust and residue material, may affect the overall performance of the device.

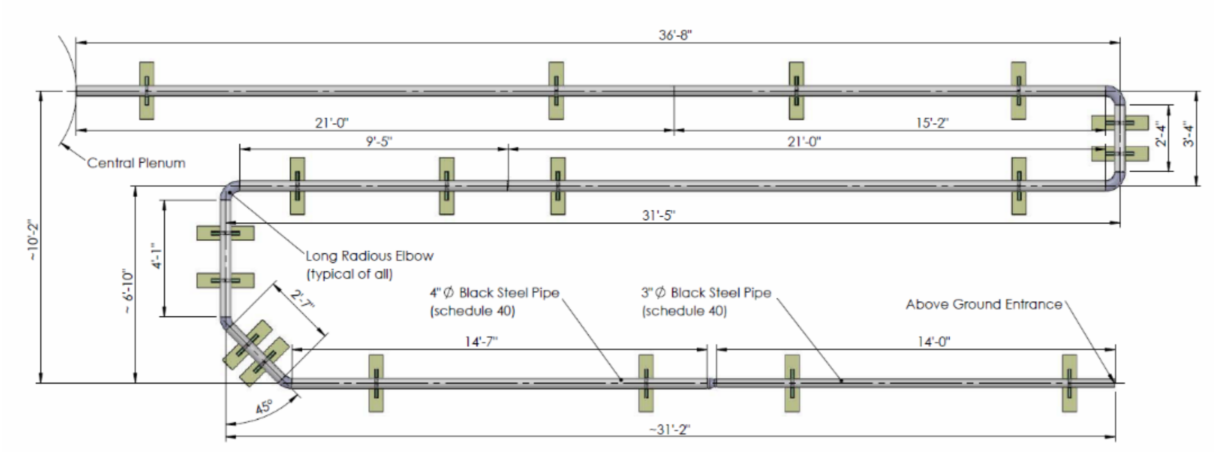

Fig. 19. Layout of the ventilation riser mockup.

Fig. 20. Preliminary tether pull and drag testing.

Fig. 21 shows a full-scale test, in which the crawler was able to navigate through the bends and crawl through approximately 30.5 m of pipeline. Due to the tether length, the speed of the crawler was significantly decreased. It took approximately 1 second to pressurize each pneumatic line, which led to a cycle time of approximately 5 seconds. The crawler moves 3.81 cm per cycle. Thus, the speed of the system was 0.762 cm/s. The 30.5 m inspection was completed in about 1 hour and 20 minutes. The speed could be improved, however, with better timing and/or the addition of expansion modules.

Fig. 21. Full scale testing.

Another alternative is to use micro pneumatic control valves embedded in the crawler modules supplied by a tether with a single air manifold. This solution would solve the issue with the pressurization of the pneumatic lines, and would also reduce the tether diameter significantly.

CONCLUSIONS

A magnetic miniature inspection tool was designed, capable of traveling through the refractory cooling channels and provide live video feedback of the channels and tank floor of DSTs at Hanford. Lab-scale mock up tests revealed various areas for improvement such as the need for redesigned wheels to withstand the cyclic loading, the magnetic force and transverse loads when turning. Another area for improvement that was addressed was reducing the width as much as possible, and implementing a tether management system. Testing of the inspection tool has provided valuable information regarding its ability to traverse through non-ideal environments such as through concave surfaces, over gaps and over a surface with rust and weathering. The path forward includes testing the inspection tool in the full-scale mockup to examine its performance in a more realistic environment. Other areas that will be explored include integration of sensors and a deployment mechanism. A deployment mechanism will allow the tool to be deployed directly into the channel, as well as have a tether management system integrated. The inspection tool is currently fitted with a camera to provide live video feedback, though fitting it with other sensors will be explored.

A pneumatic pipe crawler that will carry out the robotic inspection of the ventilation header piping of the DSTs was also successfully designed. The device will provide real time feedback from video and several other sensors during inspection. A functional prototype was successfully manufactured and tested in bench and full-scale testbeds. Based on the results, the crawler has great potential to accomplish the proposed inspection at Hanford. The path forward for the crawler includes (a) finalizing the instrumentation module design, (b) continuing validation of the device in full scale tests, (c) continuing the modification of the design as needed, (d) developing a cable management system, (e) integrating various sensors suitable for non-destructive inspection, and (f) scaling up the design for inspecting the 15.24 cm leak detection pipeline in the DSTs. Based on the availability of time and budget, the future plans may also include designing a full electric version and scaling down the design for inspecting 5.08 cm pipelines.

REFERENCES

1. Abrahao, A., et al., Development of Inspection Tools for the AY-102 Double-Shell Tank at the Hanford DOE Site. Waste Management Symposium, 2016.
2. Lagos, L., et al., Chemical Process Alternatives for Radioactive Waste – Year End Technical Report, October 21, 2016.
3. Pribanic, T., et al., Design Optimization of Innovative High-Level Waste Pipeline Unplugging Technologies. Waste Management Symposium, 2013.